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Review Article

The Material-to-Electrode Translation in Ceramic–Carbon Hybrid Supercapacitor Electrodes: From Intrinsic Charge-Storage Capability to Practical Electrode Performance

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ABSTRACT

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Hybrid supercapacitor electrodes that combine redox-active ceramic or ceramic-related phases with conductive carbon are commonly evaluated based on material properties, such as theoretical charge-storage capability, surface area, and conductivity, alongside measured electrode properties, such as capacitance and rate capability. However, these descriptors do not directly determine practical electrode performance. This review argues that a material-to-electrode translation pathway separates intrinsic charge-storage capability from the measured electrode response. This pathway encompasses hybrid integration, electrode architecture and interfaces, and coupled electron and ion transport. Electrolyte accessibility, reaction distribution, and active-material utilization link these features to practical electrode capacitance, while degradation can alter these conditions during cycling. Carbon is therefore considered part of a functional electrode framework rather than merely a conductive additive. It can provide electronic pathways, influence pore connectivity and electrolyte access, support interfacial contact, and affect the spatial distribution of the ceramic phase. This review synthesizes these coupled effects across ceramic–carbon hybrid electrodes and distinguishes material-level potential from electrode-level utilization and practical performance. Particular attention is given to the effects of electrode thickness, active-material loading, tortuosity, interfacial quality, and reaction heterogeneity. A translation-aware design framework is proposed to connect intrinsic material selection with specified loading, condition-dependent utilization, cycling stability, and independently validated device performance. This perspective shifts electrode development from the isolated optimization of material descriptors toward testable comparisons of the factors that enable or limit active-material participation.

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1. INTRODUCTION: THE MATERIAL-TO-ELECTRODE TRANSLATION PROBLEM

Supercapacitors have attracted considerable attention as electrochemical energy-storage systems because of

their high power capability, rapid charge–discharge response, and long operational lifetime. However, their charge-storage performance depends strongly on electrode architecture and the manner in which electrochemically active materials are integrated into

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functional electrodes ([Ge et al., 2021](#); [Simon & Gogotsi, 2008](#)). In this review, “material-to-electrode translation” describes how the charge-storage capability of a ceramic or ceramic-related active phase is expressed in the measured response of a ceramic–carbon electrode under specified compositional, architectural, loading, and testing conditions.

[Y. Wang and Xia \(2013\)](#) review the progression from material design to supercapacitor construction. [Y. Wang et al. \(2016\)](#) examine electrochemical-capacitor mechanisms, materials, and characterization, whereas [Yan et al. \(2014\)](#) focus on design and fabrication strategies for achieving high energy density. Collectively, these reviews address material selection, charge-storage mechanisms, electrode fabrication, and device design.

The combination of rapid charging and repeated power delivery also explains the role of electrochemical capacitors in energy-management applications ([Miller & Simon, 2008](#)).

Ceramic and ceramic-related materials, including transition-metal oxides, mixed-metal oxides, hydroxides, sulfides, carbides, nitrides, and MXene-type two-dimensional transition-metal carbides and nitrides, offer diverse opportunities for Faradaic and pseudocapacitive charge storage. Their electrochemical behavior can arise from multiple oxidation states, surface redox reactions, ion insertion or intercalation, and surface functional groups ([G. Wang et al., 2012](#); [Ren et al., 2021](#)). However, the intrinsic electrochemical potential of these materials does not necessarily translate into a proportional increase in the capacitance of a practical electrode. Limited electronic conductivity, restricted ion transport, inaccessible active sites, sluggish reaction kinetics, and structural instability can limit the measured response under specified electrode configurations and testing conditions ([Ge et al., 2021](#); [Gopi et al., 2024](#)).

Recent reviews of transition-metal oxide supercapacitor electrodes examine these challenges in terms of oxide selection, electrode structure, and electrochemical evaluation ([Gaikwad et al., 2024](#)).

[Parvin et al. \(2025\)](#) reviewed hybrid-supercapacitor materials alongside scalable fabrication techniques. Their emphasis on fabrication complements the electrode-level translation framework considered here.

Hybridization with carbon is therefore widely employed to address some of these limitations. Carbon phases can provide electronically conductive networks, interconnected pore structures, improved electrolyte penetration, and mechanical support for redox-active phases ([Ren et al., 2021](#); [Salanne et al., 2016](#); [Zhi et al., 2013](#)). Nevertheless, simply combining an active material with carbon does not guarantee effective hybridization or improved electrode performance. The spatial distribution of the active phase, continuity of the carbon network, nature and density of ceramic–carbon interfaces, and resulting pore and transport pathways

influence which regions of the active phase remain electronically connected and electrochemically accessible during operation. Accordingly, carbon should be regarded not merely as a conductive additive but as a component of the electrode architecture that influences how material properties contribute to the measured response.

Carbon–metal oxide composites are therefore best assessed by considering the combined roles of the carbon support and the redox-active oxide rather than oxide composition alone ([Zhi et al., 2013](#)).

The central issue, therefore, is not simply whether a material possesses favorable electrochemical properties, but how effectively those properties translate into practical electrode performance. In a hybrid electrode, this translation involves a sequence of coupled processes extending from the active phase to the electrode and ultimately to the device. Intrinsic redox chemistry and electronic structure establish the initial charge-storage potential, whereas ceramic–carbon integration determines how the active phase is incorporated into the electrode. Electrode architecture and interfaces influence the pathways available for electron and ion transport. Coupled transport and electrolyte accessibility determine which regions can be reached within the relevant timescale, while the resulting reaction distribution influences active-material participation under specific operating conditions. Figure 1 summarizes how material properties, electrode organization, and operating conditions collectively shape the measured response.

An important consequence of this perspective is that active-material utilization should be treated as an electrode-level outcome rather than a fixed intrinsic property. The total mass of an active phase does not necessarily correspond to the amount of material that contributes to charge storage. Conceptually, the contribution of the incorporated active phase depends on electrolyte accessibility, electronic connectivity, and its ability to respond within the measurement timescale. These distinctions are conceptual rather than independently measured numerical fractions unless an appropriate reference and measurement method are defined. Limitations at any stage of this pathway can result in a translation loss between intrinsic charge-storage capability and measured practical capacitance ([Ge et al., 2021](#); [Mazloomian et al., 2026](#)).

The same framework provides a basis for understanding performance degradation. During repeated cycling, structural reconstruction, dissolution, oxidation, pore blockage, or loss of electronic connectivity may alter the amount of active material retained, its accessibility, or its electronic connection to the conductive network. Degradation is therefore an important consideration in the material-to-electrode translation pathway. However, a decline in capacitance alone cannot establish which of these changes is responsible.

Material-to-electrode translation

Where intrinsic capability becomes practical capacitance

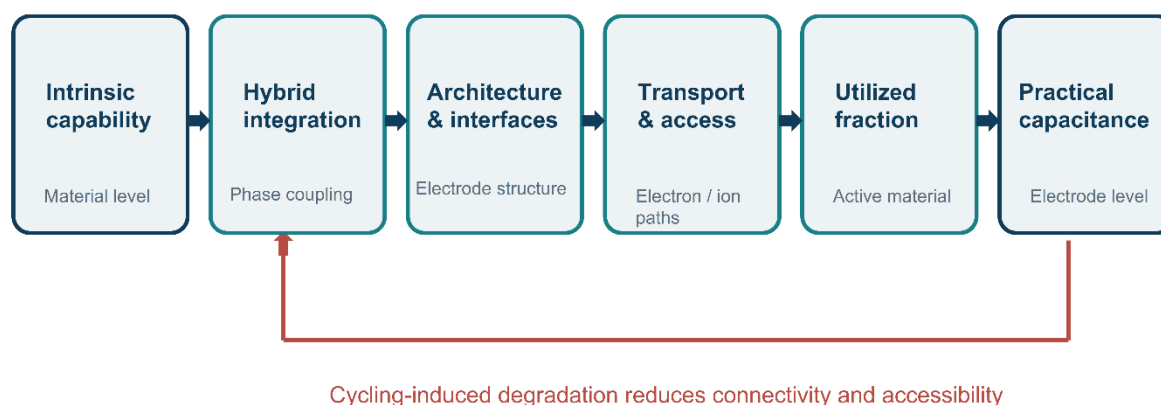


Figure 1. Material-to-electrode translation in ceramic–carbon hybrid supercapacitors. Intrinsic charge-storage capability is connected to practical electrode capacitance through hybrid integration, architecture and interfaces, coupled transport and electrolyte access, and condition-dependent active-material participation. The feedback arrow indicates that cycling-induced degradation can reduce connectivity and accessibility. The diagram is conceptual and does not imply a quantitative multiplication of the stages.

Accordingly, this review examines how the charge-storage capability of redox-active ceramic and ceramic-related phases translates into the performance of ceramic–carbon electrodes under specified operating and measurement conditions. It traces the roles of hybrid integration, electrode architecture, interfaces, transport, and active-material utilization in determining practical capacitance. Drawing on representative literature examples, the review identifies where material-level advantages may be diminished or lost at the electrode level and discusses the implications for electrode design and performance reporting. Full-cell results are considered where available.

2. INTRINSIC CHARGE-STORAGE CAPABILITY

The first step in understanding the material-to-electrode translation problem is to establish the intrinsic charge-storage capability of the active phase before its integration into a hybrid electrode. Intrinsic charge-storage capability serves as a material-level reference, based on either a theoretical estimate or an experimental response obtained under defined conditions. In contrast, practical electrode capacitance is determined from the measured response of an assembled electrode under specified testing conditions and using a defined normalization basis. Here, “measured electrode response” refers to the recorded electrochemical behavior, whereas “electrode-level performance” encompasses the metrics used to evaluate that response,

including capacitance, rate capability, and cycling stability under specified testing conditions. This distinction is particularly important for ceramic and ceramic-related redox-active materials, for which high theoretical charge-storage capability may coexist with limited electronic conductivity, restricted ion transport, sluggish reaction kinetics, or incomplete active-material utilization. Accordingly, the intrinsic properties of the active phase should be regarded as the starting point of the material-to-electrode translation pathway rather than as direct predictors of practical electrode performance (Conway, 1999; Simon & Gogotsi, 2008).

2.1. Intrinsic Charge-storage Capability Versus Measured Capacitance

The charge-storage response of supercapacitor electrodes can arise from electrostatic ion adsorption, reversible Faradaic reactions, or a combination of these mechanisms. Electric double-layer capacitance is primarily associated with charge separation at the electrode–electrolyte interface, whereas pseudocapacitive processes involve rapid, reversible Faradaic reactions coupled with ion compensation. Transition-metal oxides, hydroxides, sulfides, and related compounds can therefore provide substantial charge-storage contributions beyond purely electrostatic mechanisms (Augustyn et al., 2014; Conway, 1999; Simon & Gogotsi, 2008).

Table 1. Representative ceramic and ceramic-related active-phase families.

Active-phase family	Representative phases	Intrinsic advantages	Main intrinsic limitations	Representative references
Transition-metal oxides	RuO_2 , MnO_2 , V_2O_5 , NiO , Co_3O_4	Rich redox chemistry and multiple oxidation states	Limited conductivity in many compositions; structural/kinetic limitations	(Augustyn et al., 2014 ; Tomboc et al., 2020)
Mixed-metal oxides	NiCo_2O_4 and related spinels	Multiple redox couples; tunable electronic structure	Composition-dependent kinetics and stability	(Kazazi, 2017 ; Ren et al., 2021)
Hydroxides	$\text{Ni}(\text{OH})_2$, $\text{Co}(\text{OH})_2$, NiCo hydroxides	High redox activity and accessible surface sites	Low conductivity and phase evolution in many systems	(Kazazi et al., 2018 ; Soltanloo et al., 2020)
Sulfides/chalcogenides	NiCo_2S_4 , CoS_x , NiS	Rich redox chemistry and often higher conductivity than oxides	Chemical/structural stability and surface oxidation	(Kazazi & Faryabi, 2020 ; Ren et al., 2021)
Carbides/nitrides	TiC , Mo_2C , VN , Mo_2N	High conductivity and robust frameworks	Surface chemistry and electrolyte-dependent storage	(Farahani et al., 2025 ; Ren et al., 2021)
MXenes	$\text{Ti}_3\text{C}_2\text{T}_x$ and related phases	High conductivity; tunable terminations; ion intercalation	Restacking, oxidation, termination-dependent behavior	(Lukatskaya et al., 2013 ; Lukatskaya et al., 2017)

For MnO_2 in aqueous electrochemical capacitors, mechanistic studies distinguish ion-associated surface storage from processes involving the oxide interior ([Toupin et al., 2004](#)). The relative contributions of these mechanisms depend on the electrode configuration and electrolyte conditions.

Accordingly, the intrinsic benchmark used for comparison must be explicitly defined. It may be a theoretical estimate based on the available charge-storage sites or an experimentally observed response obtained under specified conditions. These two types of benchmarks are not interchangeable. Similarly, experimental values obtained for different ceramic phases or under mismatched testing conditions do not provide a common reference for calculating a numerical utilization percentage. Before a difference between intrinsic charge-storage capability and measured electrode capacitance is interpreted as a utilization loss, the reported quantity, mass basis, potential window, electrolyte, and measurement timescale must be considered ([Conway, 1999](#); [Ge et al., 2021](#); [Simon & Gogotsi, 2008](#)).

The theoretical charge-storage capability of an active phase should not, however, be equated with the capacitance measured for a practical electrode. Theoretical values generally assume that the relevant redox centers or ion-storage sites are accessible and that the associated reactions proceed reversibly throughout the active material. In real electrodes, only a fraction of these sites may participate within the experimental timescale because of limitations in electronic transport, ionic diffusion, electrolyte penetration, reaction kinetics, or structural stability. Consequently, experimentally measured capacitance represents an electrode-level outcome rather than a direct measure of intrinsic material potential.

This distinction is also important when the term *pseudocapacitance* is used to describe Faradaic charge

storage. Not all reversible Faradaic processes exhibit genuinely pseudocapacitive kinetics. Surface redox reactions can produce capacitive-like behavior, whereas ion insertion can exhibit either a rapid pseudocapacitive response or appreciable diffusion limitations, depending on the material and operating conditions. Therefore, classifying a material as “pseudocapacitive” solely on the basis of high capacitance or a favorable cyclic voltammetry response can obscure the underlying charge-storage mechanism ([Brousse et al., 2015](#); [Fleischmann et al., 2020](#)). Within the present framework, the relevant question is not simply how much charge an active phase can theoretically store, but how much of that intrinsic charge-storage capability remains accessible after the material is incorporated into an electrode.

Classification of a charge-storage process as pseudocapacitive should therefore be based on its electrochemical response and, where available, quantitative kinetic analysis rather than on material identity alone ([Simon et al., 2014](#); [Y. Jiang & Liu, 2019](#)).

Likewise, the presence of multiple oxidation states does not guarantee that all corresponding redox centers will participate during electrode operation. Electron transport through the active phase, charge-transfer kinetics at the electrode–electrolyte interface, and ionic compensation within the material can determine whether these redox states participate within a given timescale. This is particularly relevant to transition-metal oxides and hydroxides, many of which exhibit strong redox activity but relatively limited intrinsic electronic conductivity. Even when the thermodynamic driving force for a redox reaction is favorable, poor electronic transport can restrict the spatial extent and rate of the reaction ([Augustyn et al., 2014](#); [Fleischmann et al., 2020](#)).

A supercapacitor-specific example is the use of electrochemically rescaled NiO clusters as the positive electrode in an asymmetric device ([Jeong et al., 2015](#)).

The pretreatment modified the oxide structure before device assembly; therefore, the resulting capacitance characterizes the prepared electrode rather than constituting an electrode-independent property of bulk NiO.

The broad family of ceramic and ceramic-related materials considered for supercapacitors does not exhibit a single characteristic charge-storage mechanism or a universal intrinsic advantage. Oxides, hydroxides, sulfides, carbides, nitrides, and MXenes occupy different positions along the spectrum of redox activity, electronic conductivity, ion accommodation, and structural stability. These differences arise from their distinct electronic structures, bonding characteristics, surface chemistries, and ion-storage mechanisms, which collectively determine their intrinsic electrochemical strengths and limitations ([Augustyn et al., 2014](#); [G. Wang et al., 2012](#); [Ren et al., 2021](#)).

As summarized in Table 1, no single active-phase family simultaneously maximizes redox activity, electronic conductivity, ion accessibility, and structural stability. Transition-metal oxides and hydroxides can provide strong redox activity but often require improvements in electronic transport and structural stability. Sulfides and related chalcogenides can offer a more favorable combination of redox activity and conductivity, although stability remains an important consideration. Carbides and nitrides can provide conductive frameworks in certain compositions, but their charge-storage behavior depends strongly on surface chemistry and the specific material. MXenes combine high conductivity with tunable surface chemistry and ion-intercalation capability; however, restacking and oxidation can restrict their effective utilization ([G. Wang et al., 2012](#); [Lukatskaya et al., 2017](#); [Ren et al., 2021](#)).

Examples spanning these material families include Ni(OH)₂ nanosheets supported on a three-dimensional graphene framework ([Y. Ma et al., 2014](#)), VN nanoparticles distributed within porous carbon membranes ([Wu et al., 2018](#)), and tungsten-nitride-coated reduced graphene oxide fibers ([Salman et al., 2020](#)). These architectures illustrate different approaches to hybrid integration; however, their reported performance should not be ranked without accounting for differences in electrolyte, active-material loading, and normalization basis.

Within these material families, graphene-transition-metal sulfide composites provide examples of hybrid architectures ([Geng et al., 2018](#)), while CuO/reduced graphene oxide electrodes offer an oxide-based example investigated for hybrid supercapacitors ([Purushothaman et al., 2014](#)). These examples illustrate different material combinations but do not imply a common charge-storage mechanism.

The mechanisms by which ions participate in charge storage provide another important distinction among active phases. Charge compensation can occur

predominantly through surface or near-surface redox reactions, ion insertion into the crystal structure, or a combination of these mechanisms. Surface-controlled processes can provide rapid electrochemical responses when the active sites remain readily accessible, whereas insertion-based mechanisms can enable substantial charge storage by allowing ions to penetrate the active phase. Neither mechanism is universally superior, as its practical effectiveness depends on transport distances, reaction kinetics, structural changes, and the accessibility of the relevant sites ([Augustyn et al., 2014](#)).

Transition-metal oxides such as Nb₂O₅ demonstrate that ion insertion does not necessarily result in sluggish electrochemical behavior. Under appropriate structural conditions, rapid and reversible ion insertion can exhibit pseudocapacitive characteristics. This behavior illustrates why the distinction between surface-controlled and insertion-related charge storage should be based on the underlying mechanism rather than simply on the presence or absence of ion diffusion ([Augustyn et al., 2014](#)).

Defects such as vacancies, lattice distortions, substitutional species, and local disorder can modify the electronic structure and surface chemistry of redox-active materials. Depending on their type, concentration, and spatial distribution, defects may alter charge density, oxidation-state stability, ion mobility, and the local energetic environment of electrochemically active sites. Consequently, defect engineering has become an important strategy for modifying the charge-storage behavior of ceramic and related electrode materials.

For oxygen-vacancy-rich Co₃O₄/graphene, calculations associated surface vacancies with electronic states that could facilitate charge transfer, alongside experimental measurements of rate performance ([S. Yang et al., 2018](#)). The proposed mechanism, however, is specific to the investigated composite and defect configuration.

Surface chemistry directly influences interactions between the active phase and the electrolyte. Surface functional groups, coordination environments, vacancies, and oxidation states can modify ion adsorption, desolvation, charge transfer, and the local energetics of Faradaic reactions. These factors are particularly important for low-dimensional materials, in which a large fraction of the active material lies near an interface.

MXenes provide a representative example of how surface chemistry and electrode architecture jointly influence charge storage. Cation intercalation has been demonstrated in layered titanium carbide ([Lukatskaya et al., 2013](#)), while deliberately engineered MXene electrodes have achieved rapid pseudocapacitive charging ([Lukatskaya et al., 2017](#)). These findings do not imply that every surface or interlayer site remains accessible at arbitrary electrode thicknesses, charging rates, or electrolyte compositions.

Reviews of MXene nanocomposites emphasize that composition and structural design influence energy-storage performance. Accordingly, intrinsic conductivity alone should not be used as a proxy for electrode-level accessibility ([Z. M. Qiu et al., 2022](#)).

Material descriptors must therefore be interpreted collectively. A large surface area does not guarantee high capacitance if the relevant sites are electronically disconnected or inaccessible to the electrolyte. Similarly, a low charge-transfer resistance characterizes a particular electrochemical state but does not directly establish active-material participation throughout a thick electrode. Figure 1 distinguishes intrinsic charge-storage capability from electrode response, while the following sections examine the roles of architecture, transport, and loading.

3. CERAMIC-CARBON HYBRIDIZATION: FROM MIXING TO FUNCTIONAL INTEGRATION

The intrinsic charge-storage capability of a ceramic active phase establishes its potential for electrochemical energy storage, but realizing this potential in a practical electrode requires effective integration with electrically conductive and ion-accessible components. Carbon is therefore widely incorporated into redox-active ceramic electrodes to compensate for limited electronic conductivity, facilitate charge transport, improve electrolyte accessibility, and provide structural support. However, the mere presence of carbon does not ensure effective hybridization. The electrochemical benefits of hybridization depend strongly on how the two phases are connected, distributed, and coupled within the electrode structure ([Ren et al., 2021](#); [Tomboc et al., 2020](#)).

From the material-to-electrode translation perspective adopted in this review, ceramic-carbon integration is the first stage in determining how the active phase contributes to electrode performance. At this stage, the central question is not simply whether carbon has been added to a ceramic active phase, but whether the resulting composite creates connected and accessible regions in which the active phase can participate in electrochemical reactions. This distinction separates conventional compositional blending from functional integration. Figure 2 illustrates the structural question at this interface: whether the two phases merely coexist or form a connected composite in which the ceramic domains remain accessible. The schematic illustrates these arrangements conceptually and does not establish their relative performance.

Ceramic-carbon electrodes can be prepared through physical mixing, co-deposition, in situ growth, layer-by-layer assembly, and other integration strategies. These approaches can produce electrodes with similar nominal compositions but substantially different electrochemical behavior. In a simple physical mixture, ceramic particles and carbon domains may coexist without forming

continuous electronic pathways or intimate interfacial contacts. Particle aggregation, phase segregation, and isolated active regions may therefore persist even when the overall carbon content is sufficient to increase the nominal electrical conductivity of the electrode. However, the fabrication method alone cannot establish whether such limitations are present in a particular electrode.

Examples of these integration strategies include NiO nanoparticles embedded in electrospun porous carbon nanofiber films ([Q. Li et al., 2018](#)) and amorphous nickel sulfide deposited on nitrogen-doped graphene nanotubes ([Meng et al., 2020](#)). These studies demonstrate fabrication routes for supporting active phases on conductive carbon structures rather than establishing a universal magnitude of the benefits of hybridization.

Other reported preparation strategies include solvothermal impregnation or coating of carbon nanotubes with nickel hydroxide ([L. Jiang et al., 2016](#)), mechanochemical coupling of Co₃O₄ nanocrystals with exfoliated graphene ([Y. Jiang et al., 2020](#)), and conversion of graphene/Co-metal-organic framework (MOF) precursors into porous carbon/Co₃O₄ composites ([S. Li et al., 2020](#)). These approaches differ in how the active phase is distributed within the carbon structure.

Functional integration, by contrast, requires more than the coexistence of the two phases. It implies that the carbon phase establishes sufficiently continuous electronic pathways, the ceramic phase is distributed within an accessible environment, and the ceramic-carbon interface provides effective electrical coupling. The resulting structure should therefore be regarded as a coupled network rather than a mixture of two independent components. This distinction is particularly important for redox-active ceramics because increased conductivity can translate into greater charge storage only if electrons and electrolyte ions can simultaneously reach the relevant active sites ([Ren et al., 2021](#); [Tomboc et al., 2020](#)).

Binder-free deposition provides further examples of active-phase integration. [Kazazi \(2017\)](#) prepared nanoflake-structured NiO/carbon nanotube composite films using electrophoretic deposition. In a different oxide system, [Kazazi et al. \(2018\)](#) investigated electrodeposited porous Co₃O₄ films on graphite electrodes modified with carbon nanotubes. These studies concern different active phases and should not be treated as a direct comparison of NiO-based systems. Both illustrate approaches to integrating an oxide with a conductive support.

The most commonly recognized role of carbon in hybrid supercapacitor electrodes is to provide an electrically conductive network. Many redox-active ceramics possess substantial charge-storage capability but relatively low electronic conductivity. When these materials are incorporated into a carbon framework, the conductive phase can reduce the effective electron-

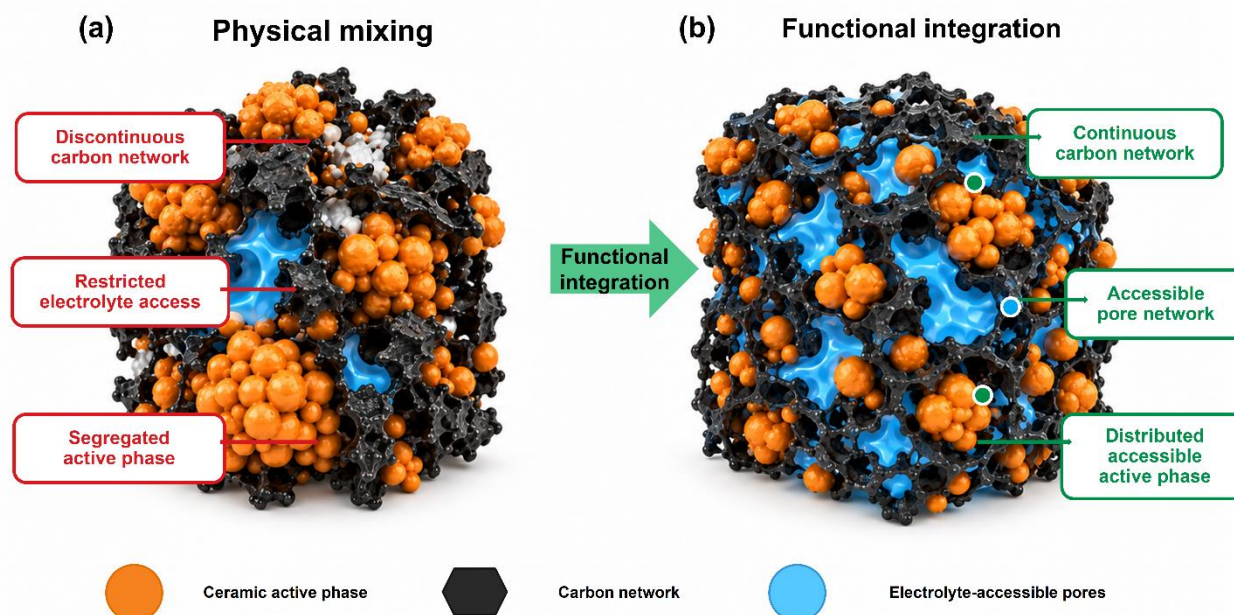


Figure 2. Conceptual comparison of (a) physical mixing and (b) functional integration in a ceramic–carbon hybrid electrode. The integrated arrangement combines a continuous carbon network, an electrolyte-accessible pore network, and spatially distributed active-phase domains. Orange, dark gray, and blue represent the ceramic active phase, carbon network, and electrolyte-accessible pores, respectively. The schematic does not represent microscopy or establish a numerical performance advantage.

transport distance between active sites and the current collector. Carbon can therefore function as an electronic backbone that enables redox-active regions to participate more effectively in electrochemical reactions ([Ren et al., 2021](#)).

Reviews of carbon-based supercapacitor electrodes ([Y. Wang et al., 2021](#)) and flexible carbon nanotube supercapacitors ([L. Liu et al., 2018](#)) provide complementary insights into the selection of carbon frameworks and their mechanical configurations.

Electronic connectivity within a hybrid electrode depends not only on the presence of a carbon network but also on the quality of contact between the carbon and ceramic phases. A ceramic particle that is geometrically close to a conductive carbon domain may still exhibit poor electronic coupling if the actual contact area is small, discontinuous, or separated by an electrically resistive interphase.

Carbon–metal oxide interactions are an important factor in determining charge-transfer behavior in hybrid supercapacitor electrodes. Stronger interactions can facilitate electronic communication between the conductive and redox-active phases, whereas weak physical contact can introduce additional interfacial resistance and limit the effectiveness of the carbon network (Soltanloo et al., 2020; Tomboc et al., 2020). The specific electrochemical roles of these interfaces are examined in Section 5 ([Ren et al., 2021](#)).

The distinction between physical mixing and functional integration is also discussed in reviews of strongly coupled inorganic–nanocarbon hybrids, which describe how growth on functionalized carbon can influence particle attachment, morphology, and charge transport ([H. Wang & Dai, 2013](#)).

Tightly coupled MnO_2 –graphene composites provide a further example of an integrated oxide–carbon architecture evaluated for supercapacitor energy and power performance ([C.-Y. Chen et al., 2012](#)). Self-assembled NiCo_2O_4 –reduced graphene oxide composites have also been compared with physically mixed NiCo_2O_4 and graphene, illustrating how the assembly route can affect the measured electrochemical response of the composite ([H.-W. Wang et al., 2011](#)).

Thus, the relevant question at this stage of the material-to-electrode translation pathway is not simply whether a carbon phase is present, but whether the assembled phases establish effective electronic contact while maintaining electrolyte accessibility to the active phase.

The second major function of carbon concerns electrolyte accessibility. A conductive carbon network can improve electron transport while simultaneously providing interconnected pores through which electrolyte ions can penetrate the electrode. This dual role makes carbon particularly valuable for redox-active ceramics whose electrochemical response is limited by both electronic and ionic transport. Three-dimensional graphene-supported hybrid structures have likewise been

employed to combine conductive scaffolds with redox-active phases ([Kazazi & Faryabi, 2020](#)).

Nevertheless, increasing the carbon content or decreasing pore dimensions does not automatically improve electrolyte accessibility. Carbon domains may occupy pore volume that would otherwise be available to the electrolyte, while excessive deposition of carbon or active material can partially block interconnected pores. Consequently, an electrode may exhibit a high nominal surface area but limited effective accessibility within the measurement timescale. The effects of electrode-scale pore architecture and coupled transport on accessibility are addressed in Sections 4 and 6.

Layer-by-layer chemical deposition has also been used to prepare a nickel hexacyanoferrate/graphene oxide (NiHCF/GO) hybrid electrode with reported improvements in supercapacitive performance ([Farahani et al., 2025](#)).

4. HYBRID ARCHITECTURE: CONTROLLING WHERE THE ACTIVE PHASE IS ACCESSIBLE

Functional integration of a ceramic active phase with a conductive carbon component establishes the basic connectivity required for electrochemical operation, but integration alone does not determine how effectively the active material is utilized throughout the electrode. Once the ceramic and carbon phases are incorporated into a hybrid system, their spatial organization becomes a critical determinant of electrolyte penetration, transport distances, reaction distribution, and, ultimately, active-material utilization. Thus, electrode architecture represents the next stage in the material-to-electrode translation pathway after hybrid integration ([Ge et al., 2021](#); [Ren et al., 2021](#)).

Electrodes containing the same ceramic and carbon components can exhibit substantially different electrochemical responses when their active-phase distribution, pore structure, thickness, or connectivity differs. A composition that is homogeneous at the macroscopic scale does not necessarily exhibit uniform electrochemical accessibility at the microscopic scale. Conversely, a deliberately organized architecture can shorten transport pathways and maintain access to a larger fraction of the active phase ([Ge et al., 2021](#); [Kress et al., 2026](#)). Recent studies of hybrid supercapacitor electrodes increasingly emphasize dimensional and hierarchical engineering to coordinate electron transport, ion diffusion, and active-material distribution rather than optimizing these characteristics independently ([Lyu et al., 2019](#); [Ren et al., 2021](#); [Z.-H. Huang et al., 2018](#)). The combined architecture-participation schematic in Section 7 illustrates these potential spatial effects without presenting them as a measured reaction profile.

Three-dimensional scaffolds provide several strategies for distributing redox-active phases. [Junaqani et al. \(2022\)](#) investigated chemically deposited β -Ni(OH)₂

nanoflakes on a three-dimensional graphene oxide framework, whereas [Kazazi et al. \(2023\)](#) examined electrodeposited cobalt oxide nanoflakes on a related framework. High-loading MnO₂ architectures studied by [Z.-H. Huang et al. \(2018\)](#) and CNT/MnO₂/graphene-grafted carbon cloth electrodes investigated by [Lyu et al. \(2019\)](#) address the additional challenge of incorporating substantial active-material mass. These examples underscore the importance of evaluating transport at the intended loading but do not establish a universal utilization benefit for all three-dimensional structures.

A reported Co₃O₄/graphene-framework composite provides a further example of integrating an oxide phase with a three-dimensional graphene scaffold ([Bao et al., 2017](#)).

The architectural literature encompasses three-dimensional carbon networks ([H. Jiang et al., 2013](#)), graphene and graphene oxide aerogels ([Korkmaz & Kariper, 2020](#)), and carbon supports ranging from zero- to three-dimensional structures coupled with redox-active materials ([Kumar et al., 2021](#)). These classifications describe available structural strategies, but their suitability depends on the required active-material loading and transport conditions. [Thiruppathi et al. \(2020\)](#) also reviewed three-dimensional graphene-based nanomaterials for energy-storage applications.

Architectural effects become particularly important as active-material loading increases. At low loading, most active domains may remain close to the external electrolyte and current-collector interfaces. As loading increases, however, overlapping domains, pore blockage, and longer transport pathways become more likely. Consequently, increasing the amount of active material does not necessarily produce a proportional increase in usable charge storage ([Ge et al., 2021](#); [Lyu et al., 2019](#); [Z.-H. Huang et al., 2018](#)).

An effective hybrid architecture should provide transport pathways across multiple length scales. Depending on their connectivity and the electrolyte properties, larger pores may facilitate electrolyte penetration into the electrode, whereas smaller accessible pores can provide interfacial area and pathways closer to active surfaces. Pore size alone, however, does not establish these functions. The carbon framework must also provide continuous electronic pathways across the electrode thickness ([Kress et al., 2026](#); [Ren et al., 2021](#)).

Metal-organic framework (MOF)-derived nanoporous carbons offer another route to tailoring porous architectures through precursor selection and conversion conditions ([Salunkhe et al., 2016](#)). Their structural tunability provides a design opportunity, but it does not establish that all resulting pores remain electrochemically accessible.

Carbon-only structural controls include free-standing nitrogen-doped hierarchical carbon foams ([J. Chen et al., 2016](#)), biochar-derived carbons with micro-, meso-, and macroporosity ([Z. Qiu et al., 2018](#)), and porous crumpled

graphene ([Tang et al., 2018](#)). These materials help establish an architectural basis for comparison without attributing carbon-based electric double-layer charge storage to the ceramic phase.

The effect of architecture ultimately depends on whether it provides connected pathways to the active phase at the intended loading and operating rate. These pathways influence reaction distribution and the fraction of active material that contributes to charge storage. The underlying transport processes are examined in Section 6.

An important consequence is that a short transport distance is not equivalent to high porosity. A highly porous electrode may still contain poorly connected pores or dead-end pathways, whereas a moderately porous but well-connected architecture may facilitate more effective ion transport. Similarly, increasing the total surface area does not necessarily increase the electrochemically accessible surface area if a substantial fraction of the pores cannot be reached within the operating timescale ([Kress et al., 2026](#); [Yuan et al., 2024](#)).

Low-tortuosity supercapacitor architectures have been investigated using solvent-exchange-assisted printing of thick electrodes ([Yuan et al., 2024](#)) and open-windowed hollow-carbon structures ([C. Wang et al., 2026](#)). Together with the pore-network analysis reported by [Kress et al. \(2026\)](#), these studies underscore the importance of controlling pathway geometry rather than relying on porosity alone. Their quantitative results, however, should not be directly extrapolated to different ceramic-carbon compositions.

The importance of architecture becomes clearer when electrochemical reactions are considered spatially rather than as a single electrode-averaged process. In a well-connected thin electrode, ions and electrons may reach most active regions with relatively small differences in local transport conditions. As the electrode becomes thicker or more densely packed, however, the local electrochemical environment can vary substantially with position ([Ge et al., 2021](#)).

Increasing active-material loading is desirable in practical applications because it can increase the amount of stored charge per geometric area. However, higher loading can increase ion-transport distances and the likelihood of pore blockage, active-phase aggregation, and nonuniform reaction distribution. Comparisons based exclusively on low-loading electrodes can therefore provide an incomplete picture of how an architecture will perform under practical conditions ([Lyu et al., 2019](#); [Z.-H. Huang et al., 2018](#)).

Within the present framework, increasing loading can be regarded as a translation stress test. An architecture that maintains accessibility as loading increases provides stronger evidence of sustained electrode-level utilization than one whose response declines sharply with increasing thickness, provided that composition and testing

conditions remain comparable ([Ge et al., 2021](#); [Lyu et al., 2019](#); [Z.-H. Huang et al., 2018](#)).

Recent studies of thick electrodes further demonstrate that architecture can be deliberately designed to reduce the transport penalty associated with increased thickness. Low-tortuosity structures and engineered transport pathways can enable thicker electrodes to maintain comparatively efficient ionic transport. These findings illustrate that thickness is not necessarily the limiting factor in itself; rather, the decisive issue is how electrode thickness interacts with the transport network ([Yuan et al., 2024](#)). This design provides an architectural example but does not establish that the same improvement will occur in every ceramic-carbon hybrid.

A nanostructure is beneficial only when its geometry produces a relevant electrochemical advantage. A nanoflake can shorten ion-transport distances if its thickness is sufficiently small and its surfaces remain accessible. A nanowire can facilitate transport if it is electronically connected and exposed to the electrolyte. A hierarchical porous structure can improve accessibility if its pores are interconnected rather than isolated ([Ge et al., 2021](#); [Kress et al., 2026](#)).

The critical point is that architecture does not simply increase the number of accessible sites; it determines which regions remain accessible under the relevant operating conditions. Accessibility therefore depends on electrode thickness, active-material loading, pore connectivity, active-phase distribution, and transport distance ([Ge et al., 2021](#); [Kress et al., 2026](#)).

5. INTERFACES: THE INTERFACIAL ROUTE TO ACTIVE-MATERIAL UTILIZATION

Hybrid architecture determines where the active phase is positioned within the electrode, but charge transfer and ion compensation require functional interfacial regions. In ceramic-carbon hybrid electrodes, these interfaces include the contact between the redox-active ceramic phase and the conductive carbon network, as well as the ceramic-electrolyte and carbon-electrolyte boundaries. Their properties influence electronic coupling, ion access, charge-transfer kinetics, and the structural stability of the active phase. Consequently, the interface should not be regarded simply as a geometric boundary between two phases, but as a functional region through which the intrinsic properties of the active material contribute to electrochemical activity ([Ren et al., 2021](#)).

The importance of interfaces becomes particularly evident when electrodes with similar compositions and architectures exhibit different electrochemical responses.

Two hybrid electrodes may contain comparable amounts of ceramic and carbon yet differ in capacitance or rate capability because of differences in interfacial contact, chemical interactions, or electrolyte exposure. From the material-to-electrode translation perspective, the critical question is therefore not simply how much

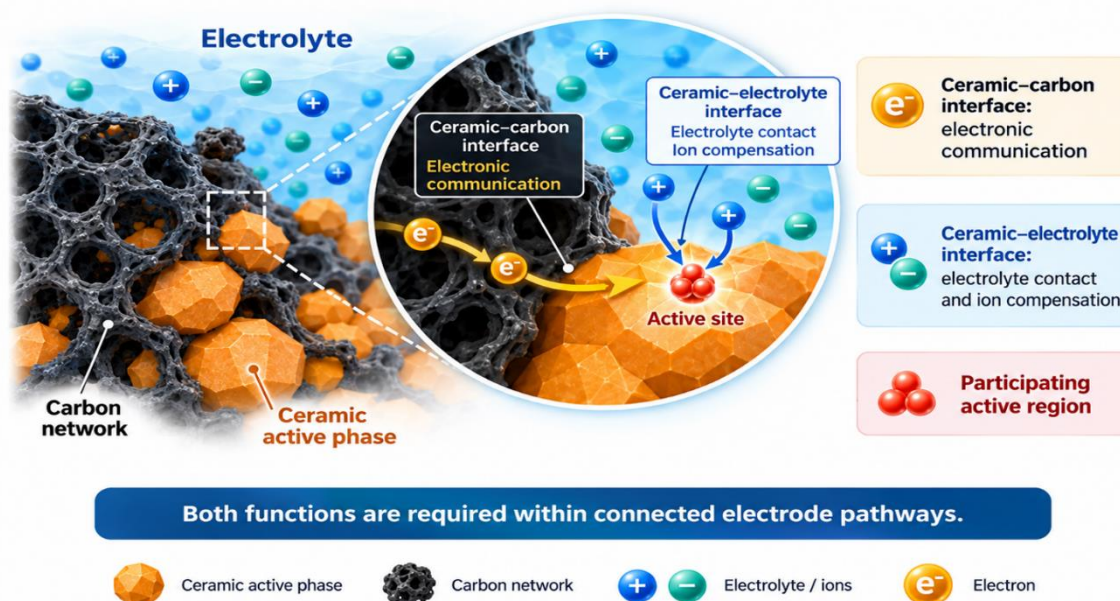


Figure 3. Complementary functions of ceramic-carbon and ceramic-electrolyte interfaces. Ceramic-carbon contact provides electronic communication, whereas the ceramic-electrolyte boundary permits electrolyte contact and ion compensation at an active region. Their coincidence within connected electrode pathways is required for participation under the operating conditions. The schematic does not assign a separate capacitance contribution to either interface.

interface exists, but whether it enables effective coupling among electrons, ions, and redox-active sites. Figure 3 distinguishes the local functions of ceramic-carbon and ceramic-electrolyte boundaries. It illustrates why electronic contact and ion access for charge compensation must coincide at electrochemically active regions; it does not quantify the contribution of either interface to capacitance.

A functional interface requires sufficiently intimate and continuous coupling between the two phases. The carbon component must provide an electronically connected environment, while the ceramic phase must remain exposed to the electrolyte to enable ion compensation and redox reactions. Thus, the electrochemical effectiveness of an interface depends on its connectivity, chemical nature, and accessibility rather than on interfacial area alone (Ren et al., 2021).

However, intimate contact must be balanced against electrolyte accessibility. Excessive coverage of the ceramic surface by carbon can improve electronic coupling while simultaneously shielding redox-active sites from the electrolyte. The most effective interface is therefore not necessarily the largest or most intimate one, but the one that maintains both electronic communication and electrochemical accessibility.

This requirement establishes an important distinction: interfacial electronic coupling is necessary for electronically mediated participation but is not sufficient

for utilization. The interface must operate within a larger network that also provides ion access and adequate reaction kinetics.

While the ceramic-carbon interface governs an important part of electronic communication, the ceramic-electrolyte interface provides a boundary at which redox-active sites can interact with the electrolyte. Charge storage in redox-active ceramics requires the movement or rearrangement of compensating ions and therefore depends on electrolyte availability at the active surface.

Structurally exposed surface area may not fully reflect electrochemical accessibility. Pore blockage, active-phase aggregation, and slow electrolyte penetration can limit the contribution of the ceramic phase under specific charge-discharge conditions. Therefore, surface area alone may not reliably indicate electrochemical utilization (Ge et al., 2021; Kress et al., 2026).

The ceramic-electrolyte interface is therefore closely linked to the architecture discussed in Section 4. Architecture determines how the electrolyte reaches the interface, while the interfacial environment influences how the available active sites participate once the electrolyte arrives. These two levels should consequently be considered coupled rather than independent.

Interface engineering can modify more than electrical resistance. In transition-metal-compound/carbon hybrids, the interfacial region may influence charge

redistribution, surface redox activity, reaction kinetics, and structural stability ([Ren et al., 2021](#)). Deliberately modifying the contact between redox-active phases and conductive components may alter electrochemical behavior beyond the effects of simple physical mixing. Such effects must be distinguished experimentally from simultaneous changes in composition or architecture.

For example, a study of graphene quantum dot/MnO₂ composites reported Mn–O–C bonding at the heterostructure interface and related the extended operating window to the interfacial region ([Jia et al., 2018](#)). This provides a concrete example of interface engineering, although the interpretation remains specific to that electrode and electrolyte.

Additional interfacial architectures investigated for supercapacitors include two-dimensional NiCrFe layered double hydroxide/MXene hybrids ([Padalkar et al., 2024](#)) and integrated NiO/NiCo₂O₄ heterojunctions coupled to a carbon layer ([H. Yang et al., 2023](#)). Given their different compositions, system-specific controls are required before performance changes can be attributed to the interface.

Nanostructuring and hybridization frequently increase the nominal interfacial area. However, maximizing interface density is not necessarily equivalent to maximizing electrochemical performance. Fine particle dispersion can generate numerous interfaces, but these may be ineffective if they are poorly connected electronically, inaccessible to the electrolyte, or associated with excessive inactive material. Reviews of quantum-dot/carbonaceous hybrids provide a broader context for this strategy in electrochemical energy storage ([Shen et al., 2020](#)). A smaller number of well-connected, electrolyte-accessible interfaces can potentially contribute more effectively than a much larger population of poorly accessible contacts. The relevant consideration is therefore the fraction of interfaces that participate in coupled electron-transfer and ion-compensation processes under operating conditions.

Quantum-dot-assisted structures also include hollow NiCo₂S₄ architectures induced by graphene quantum dots ([Y. Huang et al., 2018](#)) and lamellar Ni(OH)₂ decorated with carbon quantum dots ([Wei et al., 2017](#)). These examples expand the range of available interfacial geometries without establishing that quantum-dot addition invariably improves utilization. Interfaces between two different redox-active phases provide an additional opportunity to modify the material-to-electrode translation pathway. In heterostructured electrodes, differences in electronic structure, conductivity, surface chemistry, or redox potential can create interfacial environments that differ from those of either component alone. When coupled with carbon, these heterointerfaces can potentially influence charge transfer and electrolyte accessibility.

However, a heterointerface should not automatically be interpreted as evidence of synergistic charge storage. Demonstrating interfacial synergy requires evidence of a relevant functional change and comparisons with the individual components and, where feasible, a physical mixture. Composition, loading, architecture, and accessible area should be matched or their differences accounted for, alongside evidence linking interfacial structure or chemistry to the measured response. Where these controls are unavailable, “interface-associated improvement” is more accurate than “demonstrated synergy.”

Interfaces affect how much of the ceramic phase contributes to charge storage. The ceramic–carbon interface can provide electronic contact, while the ceramic–electrolyte interface enables ionic compensation and redox reactions. Interfacial chemistry can also affect reaction rates. In this way, interfaces help connect the ceramic’s intrinsic charge-storage capability to the measured electrode response.

These functions depend on transport within the electrode. Electrons and ions must reach the relevant sites during charging and discharging. Section 6 examines how electron and ion transport, together with electrolyte accessibility, affects active-material utilization.

6. TRANSPORT AND ELECTROLYTE ACCESSIBILITY

The intrinsic charge-storage capability of a ceramic active phase can be translated into electrode-level performance only when electrons and electrolyte ions can reach electrochemically active regions within the relevant operating timescale. In hybrid supercapacitor electrodes, transport therefore links the structural organization established by the architecture to the electrochemical reactions occurring at ceramic–electrolyte interfaces. The conductive carbon framework can facilitate electronic transport, while the interconnected pore network provides pathways for electrolyte penetration and ion movement. The effectiveness of the hybrid electrode consequently depends not on either transport pathway alone, but on their coupled ability to supply the active ceramic phase with electrons and compensating ions ([Ge et al., 2021](#); [Ren et al., 2021](#)).

Electronic and ionic transport impose different requirements on a hybrid electrode. Electrons must travel from the current collector through the carbon network and into the redox-active ceramic phase, whereas electrolyte ions must penetrate the pore network and reach the corresponding electrochemical interfaces. A well-connected electronic network cannot compensate for severely restricted ionic transport, just as high electrolyte accessibility cannot compensate for electronically isolated ceramic domains. For an active

region to contribute at a given rate, both pathways must remain effective over the relevant timescale.

This distinction becomes increasingly important as the amount of active ceramic material increases. At low loading, most active regions may be sufficiently close to both the conductive network and electrolyte pathways that transport limitations remain relatively small. With increasing loading or electrode thickness, however, transport distances can increase, and spatial differences in ion concentration and reaction rate can become more pronounced. Consequently, the same ceramic material can exhibit substantially different electrochemical utilization depending on how effectively the hybrid structure supports both electron and ion transport.

The carbon component is particularly important for maintaining electronic connectivity, but its contribution should be evaluated in relation to the ceramic phase it supports. As discussed in Section 3, increasing carbon content can improve connectivity while reducing the active-phase fraction. Here, the transport question is whether the resulting electronic pathways remain effective while preserving ion access at the intended loading and rate ([Ren et al., 2021](#)).

For electrospun carbon nanofibers, the literature also emphasizes the balance among pore development, conductivity, heteroatom modification, and mechanical robustness ([Nie et al., 2020](#)).

Reviews of graphene-based two-dimensional supercapacitor materials ([Palaniselvam & Baek, 2015](#)) and porous-carbon-supported metal/metal-oxide electrodes ([Veerakumar et al., 2020](#)) consider conductivity, support geometry, and active-phase integration as interconnected aspects of electrode design.

Electrolyte transport is strongly influenced by pore-network topology. High porosity or a large specific surface area can increase the apparent space available for electrolyte penetration, but these parameters do not necessarily indicate how effectively ions can move through the electrode. Disconnected pores, constricted pore entrances, and highly tortuous pathways can substantially increase effective transport distances even when the overall pore volume is high. Electrolyte contact with the outer surface also does not, by itself, establish that internal pores are wetted and supplied quickly enough during operation. Ceramic morphology and packing can alter the pathways available to electrolyte ions. Aggregates and densely stacked sheets may narrow pore entrances, whereas dispersed or porous ceramic domains may improve access when incorporated into a connected pore network.

Pore accessibility also depends on the compatibility between the carbon pore structure and the electrolyte. Studies of carbide-derived carbons showed that subnanometer pores can contribute to electric double-layer storage and that capacitance depends strongly on the relationship between pore and ion sizes ([Chmiola et al., 2006](#); [Largeot et al., 2008](#)). These findings, together

with broader analyses of ion solvation and electrolyte selection ([Béguin et al., 2014](#)), caution against applying a single geometric pore-size cutoff to all hybrid electrodes.

Wettability is illustrated more directly by carbon-quantum-dot-induced MnO₂ nanowire membranes, in which improved surface wetting accompanied an enhanced electrochemical response ([Lv et al., 2017](#)). However, wetting measurements alone do not quantify the charge stored at individual internal sites.

Studies of porous supercapacitor electrodes show that pore-network connectivity and tortuosity can affect ionic transport and charging rates ([Kress et al., 2026](#)). A structured thick-electrode design likewise illustrates one approach to reducing the transport penalty associated with increased thickness ([Yuan et al., 2024](#)). These findings motivate the examination of transport pathways in ceramic-carbon hybrids, but their quantitative outcomes cannot be transferred to a different composition or electrolyte without direct evidence. Carbon-only comparisons can help distinguish conductive-network design from ceramic redox chemistry. Deoxidized interconnected carbon frameworks have been studied for rapid charging ([Leng et al., 2021](#)), while graphene quantum dots have been used to improve the conductive network of activated carbon ([Qing et al., 2019](#)). These studies motivate transport-oriented controls but do not establish a ceramic contribution.

This distinction is important because conventional electrochemical measurements usually provide an integrated response from the entire electrode. High overall capacitance therefore does not reveal whether the reaction is distributed relatively uniformly throughout the active layer or concentrated within a limited region. Transport limitations and differences in local accessibility can produce heterogeneous reaction contributions, even when the measurement reports only an electrode-averaged response ([Ge et al., 2021](#); [Kress et al., 2026](#)). Claims about the actual spatial reaction profile of a particular electrode require evidence beyond its overall capacitance.

Rate capability is often interpreted as an indicator of fast electrochemical kinetics, but in hybrid ceramic electrodes, it can also serve as a practical test of transport and kinetics together. At low current density, ions and electrons have more time to penetrate the electrode and reach a larger fraction of active sites. As current density increases, transport limitations may become more apparent, and poorly connected or deeply embedded ceramic regions may contribute less to the measured charge storage.

Accordingly, a strong rate response should not automatically be attributed to high intrinsic reaction kinetics. Instead, it may reflect an effective combination of intrinsic kinetics, electronic connectivity, pore-network topology, electrolyte accessibility, and short

transport distances. This interpretation is consistent with the growing recognition that efficient pore connectivity and low tortuosity are critical for maintaining rapid charging in porous electrodes ([Kress et al., 2026](#)). Conversely, a decline in capacitance at higher current does not uniquely identify which of these factors is limiting.

Section 7 examines how accessibility and transport limitations affect the contribution of the ceramic phase to the measured electrode response.

7. FROM ACCESSIBILITY TO ACTIVE-MATERIAL UTILIZATION

Electrolyte accessibility and transport determine whether electrochemically active regions can be reached, but accessibility alone does not guarantee that the corresponding ceramic phase will contribute effectively to charge storage. The next step in the material-to-electrode translation pathway is therefore active-material utilization, which describes the contribution of the incorporated active phase to the measured electrochemical response under defined operating conditions. A numerical utilization fraction is justified only when both a compatible reference charge and the charge attributable to the ceramic phase can be established under the stated conditions. Otherwise, “active-material utilization” is used here as a condition-dependent interpretation of the ceramic phase’s contribution to the measured electrode response, not as a measured percentage. This distinction is particularly important for ceramic–carbon hybrid electrodes because increasing the amount of redox-active ceramic does not necessarily produce a proportional increase in practical capacitance ([Ge et al., 2021](#)).

The incorporated ceramic mass establishes the available inventory, but electrolyte access, electronic connectivity, and reaction kinetics influence how much of it contributes under the specified test conditions. These factors indicate possible limitations on participation but do not define independent fractions that can be multiplied to obtain a numerical utilization value. Conductivity, impedance, pore accessibility, and rate-dependent measurements may help assess these limitations, but no single measurement can generally quantify each contribution independently.

This relationship is particularly important in hybrid electrodes because the same ceramic material can exhibit substantially different utilization depending on how it is integrated with the carbon framework. A ceramic domain may be physically present but electronically isolated, electronically connected but poorly exposed to the electrolyte, or accessible to both electrons and ions but kinetically underutilized under the applied operating conditions. Active-material utilization should therefore be considered an electrode-level outcome arising from the combined effects of the preceding translation steps,

rather than an intrinsic property of the ceramic itself ([Ge et al., 2021](#)). Figure 4 distinguishes incorporated, accessible, and electrochemically contributing material. Its purpose is to identify potential losses along this progression without assigning a numerical percentage to any stage.

Active-material utilization is closely related to the spatial distribution of electrochemical reactions within the electrode. When the design goal is to use material throughout the active layer, a reaction concentrated mainly in one region indicates that other regions may contribute less under the specified conditions. In practice, variations in local pore connectivity, electronic pathways, electrolyte concentration, transport distance, and ceramic loading can cause some regions to react more strongly than others.

Electrode-averaged measurements alone do not establish how uniformly the ceramic phase participates across the active layer. Studies of material utilization and long-range ionic transport support treating access and participation as condition-dependent, but they do not, by themselves, map the local reactions of individual ceramic domains ([Ge et al., 2021](#); [Kress et al., 2026](#)). Claims about the spatial distribution of reactions in a particular hybrid electrode therefore require appropriate spatially resolved or operando evidence.

In situ diffusion NMR provides a complementary example of a transport-sensitive measurement: ion diffusion has been measured directly in carbon supercapacitor electrodes ([Forse et al., 2017](#)). Such measurements constrain the interpretation of transport behavior but do not, by themselves, quantify the utilization of a separate ceramic phase.

7.1. Mass Loading as a Utilization Challenge

Increasing the mass loading of a redox-active ceramic is an attractive strategy for increasing areal capacitance, but it simultaneously increases the demands placed on transport and reaction pathways. As the amount of active material increases, a larger fraction of the ceramic phase may become located farther from efficient ionic or electronic pathways. Consequently, utilization may decrease even while the total amount of active material increases.

This creates a fundamental distinction between active-material loading and active-material utilization. Increasing loading increases the amount of potentially charge-storing material in the electrode, whereas utilization concerns its effective contribution to the response measured under the operating conditions. The relationship between loading and areal capacitance is therefore not necessarily linear.

The effect is illustrated by high-mass-loading MnO₂ electrodes, in which increasing active-material loading can introduce substantial transport limitations because of the active phase’s limited electronic conductivity and the

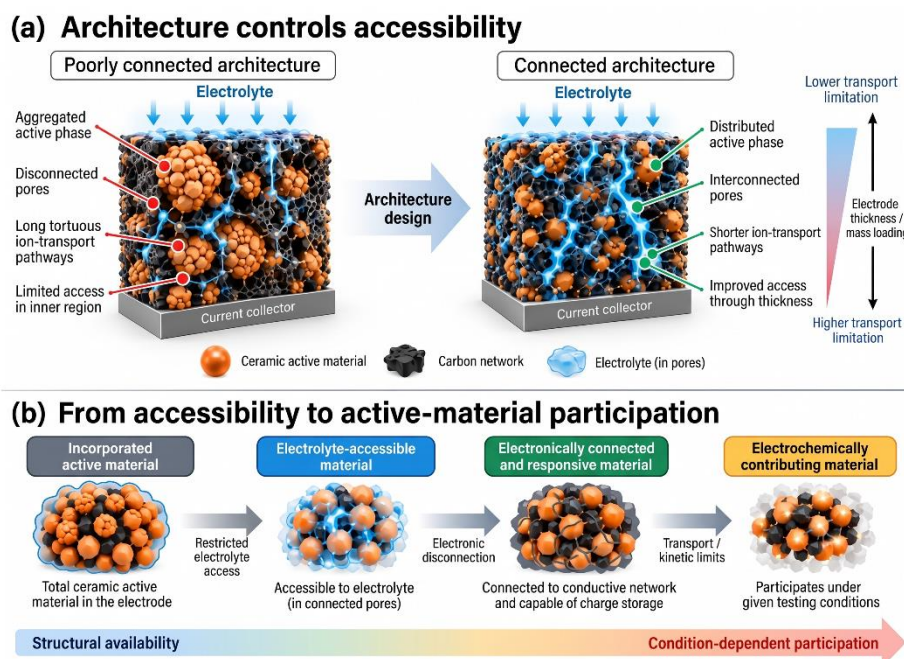


Figure 4. Architecture, accessibility, and active-material participation. (a) Poorly connected and connected architectures illustrate differences in pore continuity, active-phase distribution, and access through electrode thickness. (b) Incorporated material is distinguished conceptually from electrolyte-accessible, electronically connected and responsive, and electrochemically contributing material. Restricted electrolyte access, electronic disconnection, and transport or kinetic limitations can reduce participation. The color gradient and progression indicate conceptual trends, not measured penetration depths, utilization fractions, or spatial reaction maps.

associated transport constraints. Hierarchical nanostructuring and appropriate electrode design can mitigate these limitations and preserve a larger fraction of the active material's electrochemical response (Z.-H. Huang et al., 2018). Similarly, CNT/MnO₂/graphene-grafted carbon-cloth electrodes have demonstrated that high MnO₂ loading can be combined with favorable rate performance when electronic and ionic transport pathways are deliberately integrated into the electrode structure (Lyu et al., 2019).

Additional loading-dependent examples include conformal MnO₂ deposits on CNT-enabled textiles (L. Hu et al., 2011) and low-crystalline FeOOH electrodes tested across several mass loadings (Owusu et al., 2017). In the latter study, increasing loading reduced gravimetric capacitance while increasing the areal response, illustrating why both reporting bases must be considered together.

These examples illustrate why high loading should be regarded as a translation stress test rather than simply a performance-enhancement strategy. An architecture that achieves excellent utilization at low loading may exhibit substantial translation losses when the amount or thickness of the ceramic phase increases.

The carbon component can increase the utilization of ceramic active phases by maintaining electronic connectivity and supporting electrolyte-accessible

electrode structures. However, this contribution is inherently associated with a compositional trade-off. Increasing the carbon fraction can improve connectivity and transport while simultaneously reducing the fraction of redox-active ceramic per unit electrode mass.

This perspective also explains why the gravimetric capacitance of a hybrid electrode should not be interpreted independently of its composition and utilization. Higher capacitance may result from more effective utilization of the ceramic phase, but it may also reflect differences in active-material fraction, loading, or measurement conditions. The preferred carbon-to-ceramic ratio depends on the active phase, carbon architecture, loading, electrolyte, operating rate, and performance metric being optimized. Determining this ratio quantitatively requires a controlled composition series that assesses the carbon contribution, electronic conductivity, electrolyte accessibility, and mass- and area-normalized responses under matched conditions (Ge et al., 2021; Ren et al., 2021).

Active-material utilization is not a fixed characteristic of a ceramic-carbon electrode; it depends on the conditions under which the electrode operates. Current density, scan rate, electrolyte composition, electrode thickness, active-material loading, and cycling history can all influence the fraction of the ceramic phase that contributes to charge storage.

This condition dependence is particularly important when comparing reported specific capacitances. A high gravimetric capacitance measured at low active-material loading and low current density does not necessarily demonstrate efficient utilization under conditions relevant to a practical, high-loading electrode. Meaningful assessment therefore requires considering loading, operating rate, and retained electrochemical response together.

This interpretation also provides a more rigorous basis for comparing hybrid electrodes. An increase in measured capacitance should not automatically be interpreted as evidence of improved material utilization. Differences in active-material fraction, loading, electrode thickness, current density, normalization method, and electrolyte conditions can all influence the reported value. These conditions must be specified before a performance difference can be attributed to improved utilization.

Section 8 examines how condition-dependent participation is expressed and reported as practical electrode capacitance.

8. TRANSLATING UTILIZATION INTO PRACTICAL CAPACITANCE

The ceramic phase's contribution can be evaluated from the measured electrode response under specified test conditions, provided that contributions from other electrode components are considered. However, practical capacitance should not be regarded as a direct representation of the ceramic material's intrinsic charge-storage capability. Rather, it is the experimentally accessible outcome of the preceding translation steps, including hybrid integration, architecture, interfacial coupling, transport, electrolyte accessibility, and active-material utilization. Consequently, the capacitance reported for a hybrid electrode reflects not only the charge that the ceramic phase can store, but also how effectively the electrode enables that capability to be expressed under defined operating conditions. The reported value also depends on how the response is calculated and normalized ([Gogotsi & Simon, 2011](#); [Noori et al., 2019](#)).

8.1. From Intrinsic Capability to Practical Capacitance

The comparisons of supercapacitor electrodes often rely on specific capacitance expressed in F g^{-1} . This parameter is useful for comparing materials under controlled conditions, but it can be misleading when interpreted independently of active-material loading, electrode thickness, current density, and electrode composition. The mass used in the denominator—ceramic active phase, ceramic-carbon composite, or total electrode—must also be specified. A high specific capacitance does not necessarily indicate a high practical

charge-storage contribution at the device or application level ([Gogotsi & Simon, 2011](#); [Noori et al., 2019](#)).

For a ceramic-carbon hybrid, the measured capacitance is influenced by at least three interconnected factors: the intrinsic charge-storage capability of the ceramic phase, the fraction of that phase that is effectively utilized, and the conditions under which the measurement is performed. Thus, a ceramic with high intrinsic redox activity may exhibit only moderate electrode-level capacitance if its utilization is poor, whereas a less intrinsically active phase may deliver a strong practical response when a larger fraction of its active material is effectively utilized ([Ge et al., 2021](#)).

This relationship is conceptual, not a multiplication rule: a theoretical material value and a measured electrode capacitance cannot be combined using an undefined utilization factor. The quantities, reference state, voltage window, and normalization basis must first be made compatible. Practical capacitance remains an electrode-level outcome rather than an intrinsic constant of the ceramic ([Ge et al., 2021](#); [Noori et al., 2019](#)).

8.2. Gravimetric Capacitance Versus Areal Capacitance

The normalization basis used to report capacitance strongly influences the interpretation of electrode performance. Gravimetric capacitance, typically expressed in F g^{-1} , is particularly useful for evaluating an active material's electrochemical contribution when the mass basis and test conditions are comparable. However, it can favor electrodes with low active-material loading because transport distances are short and a large fraction of the material may be utilized.

Areal capacitance, expressed in F cm^{-2} , provides a different perspective because it represents measured capacitance per unit of geometric electrode area. Increasing active-material loading can therefore increase areal capacitance even when gravimetric capacitance decreases. For values obtained from the same measurement and using the same mass basis, areal capacitance equals gravimetric capacitance multiplied by the corresponding mass loading. This accounting relationship does not imply that every increment of added material is equally utilized. This distinction illustrates why maximizing F g^{-1} and maximizing practical electrode performance are not necessarily identical objectives ([Noori et al., 2019](#)).

High-loading ceramic electrodes provide an important test of this distinction. Hierarchical MnO_2 architectures, for instance, demonstrate that substantial active-material loading can be combined with improved utilization when the electrode structure maintains effective transport pathways ([Z.-H. Huang et al., 2018](#)). Similarly, CNT/MnO_2 /graphene-grafted carbon-cloth electrodes demonstrate the importance of integrating conductive and porous frameworks when designing high-energy

asymmetric supercapacitors ([Lyu et al., 2019](#)). These examples represent specific electrode designs; their measured values should be compared only when the reporting basis is explicit and consistent.

The relationship between active-material loading and capacitance is one of the clearest manifestations of the material-to-electrode translation gap. At low loading, a relatively large fraction of the ceramic phase may remain accessible and electrochemically active. Increasing loading can initially increase areal capacitance because more active material is incorporated into the electrode. Beyond a system-dependent range, however, additional material may experience increasingly severe transport limitations and incomplete utilization.

As a result, areal capacitance may increase sublinearly with increasing mass loading. In some cases, the additional ceramic contributes relatively little to the total measured response because it occupies poorly accessible regions.

The relevant design objective is therefore not simply to maximize loading, but to identify a loading that delivers the required areal response and rate performance under the intended test conditions.

Practical capacitance also depends strongly on the rate at which the electrode is charged and discharged. At low current density or scan rate, ions and electrons may have more time to reach a larger fraction of the active ceramic. At higher rates, the time available for transport and reaction decreases, and the measured capacitance increasingly reflects the fraction of material that can respond rapidly.

This interpretation reinforces the importance of considering capacitance alongside current density and loading rather than treating a single capacitance value as a universal material descriptor.

8.3. Practical Capacitance and Volumetric Considerations

The translation problem becomes even more evident when volumetric performance is considered. Increasing porosity can improve electrolyte accessibility and reduce transport limitations, but excessive void volume can reduce the amount of active material accommodated within a given electrode volume. Conversely, dense electrodes can provide high volumetric active-material content while restricting electrolyte penetration and increasing transport distances.

Dense, integrated hybrid electrodes, including RuO₂/graphene systems, have been reported to exhibit high volumetric capacitance ([H. Ma et al., 2017](#)). The volume used for normalization, such as that of the active layer or the complete electrode, must be identified before reported values can be compared ([Noori et al., 2019](#)).

Volumetric performance has also been examined in thin, self-supporting CoZnNiS/CNT/graphene films ([Y. Liu et al., 2021](#)) and densely packed holey-graphene

frameworks ([Xu et al., 2014](#)). The former represents a hybrid active-phase system, whereas the latter is a carbon-only architectural example. Neither eliminates the need to specify the volume and device components included in the normalization.

Fe₂O₃ nanoparticle-cluster/rGO paper electrodes have also been evaluated as flexible negative electrodes using volumetric metrics ([Y. Hu et al., 2016](#)). This is particularly relevant when replacing a carbon-only negative electrode because introducing an additional redox-active phase changes both the composition and the occupied volume.

Table 2 presents selected high-loading MnO₂–carbon electrodes alongside the conditions under which their reported areal responses were obtained. These examples illustrate how loading, rate, electrolyte, and normalization affect interpretation; differences across studies do not constitute a controlled ranking of architectures.

The values are transcribed from the cited studies and retain their original testing bases. The area-normalized electrode values are not directly comparable because the scan rate or current density, electrolyte, architecture, and cell configuration differ. Missing or unverified parameters are not inferred. Device energy densities are reported using the volume bases specified by the respective authors and should not be equated with electrode capacitances.

For reproducible electrode comparisons, reports should specify active-material loading, electrode thickness and composition, the mass and volume used for normalization, electrolyte and potential window, current density or scan rate, testing configuration, and rate-dependent capacitance. Areal and volumetric values should also be included where relevant. Cycling retention should be reported alongside the corresponding test conditions rather than as an isolated percentage ([Gogotsi & Simon, 2011](#); [Noori et al., 2019](#)).

Under comparable test conditions, effective integration may allow an electrode containing a moderately active ceramic to deliver higher measured capacitance than one containing a more active ceramic with limited accessibility or connectivity. This distinction provides a more meaningful explanation for why structurally different electrodes containing the same or similar active phases can exhibit substantially different practical capacitances.

8.4. Practical Capacitance as the Electrode-level Translation Boundary

Practical capacitance represents the point at which the preceding material-to-electrode translation pathway becomes experimentally evident in electrode performance. It therefore integrates the effects of intrinsic material properties, hybridization, architecture, interfaces, transport, electrolyte accessibility, reaction

Table 2. Selected quantitative examples of high-loading MnO₂–carbon electrodes. Electrode measurements and full-cell outcomes are kept separate.

Electrode	Electrode Loading	Electrode Test	Electrode response; full-cell evidence	Representative references
MnO ₂ /CNT textile	8.3 mg MnO ₂ cm ⁻² ; thickness not specified.	0.5 M Na ₂ SO ₄ aqueous; CV, 0.05 mV s ⁻¹ .	2.8 F cm ⁻² (projected area). Full cell: MnO ₂ /CNT textile // reduced MnO ₂ /CNT textile.	(Hu et al., 2011)
MnO ₂ /carbon cloth	10 mg MnO ₂ cm ⁻² ; thickness not specified.	GCD, 3 mA cm ⁻² .	3.04 F cm ⁻² ; 304 F g ⁻¹ (MnO ₂). Aqueous and solid-state asymmetric cells: 8.3 and 8.0 mWh cm ⁻³ , respectively.	(Z.-H. Huang et al., 2018)
CNT/MnO ₂ /graphene-grafted carbon cloth	9.1 mg MnO ₂ cm ⁻² ; thickness not specified.	1 M Na ₂ SO ₄ aqueous, three-electrode; GCD, 1 mA cm ⁻² .	3.38 F cm ⁻² ; 371.4 F g ⁻¹ (MnO ₂). Full cell: CNT/MnO ₂ /GCC // V ₂ O ₅ , PVA/Na ₂ SO ₄ gel; 2.2 V, 10.18 mWh cm ⁻³ .	(Lyu et al., 2019)

distribution, and active-material utilization. For responses that exhibit strongly battery-like behavior or pronounced voltage dependence, a single capacitance value may obscure the voltage profile. In such cases, the measured charge and the method used to calculate capacitance should also be reported (Noori et al., 2019).

Section 9 develops design principles based on these electrode-level constraints, while Section 10 examines whether the resulting response is retained during cycling.

9. DESIGN PRINCIPLES FOR RETAINING ELECTRODE-LEVEL PERFORMANCE

The material-to-electrode framework developed in the preceding sections provides a basis for translating the identified mechanisms into practical design principles. Rather than treating intrinsic material properties, hybrid composition, architecture, interfaces, and transport as independent optimization targets, these parameters should be considered coupled elements of a single electrode-design problem. The objective is therefore not to maximize a single material descriptor, but to improve electrode performance under the intended loading, rate, and operating conditions while identifying the specific limitation that the design addresses. Figure 5 organizes each design decision around an observed limitation, a proposed intervention, and a response measured under comparable conditions. It presents a decision framework rather than a ranking of universally superior materials or architectures.

9.1. Design for Utilization Rather Than Maximum Intrinsic Capability

When selecting a ceramic phase, it is important to evaluate its performance within the intended architecture and at the target loading and operating rate, rather than relying on its intrinsic charge-storage capability alone (Ge et al., 2021).

9.2. Match Pathways to Loading and Operating Rate

Electrode architecture should be designed from the outset around the distances that electrons and electrolyte ions must traverse. Increasing electrode thickness or active-material loading without maintaining effective transport pathways can progressively increase reaction heterogeneity and reduce active-material utilization.

Accordingly, hierarchical structures, interconnected pore networks, aligned transport pathways, and appropriately distributed ceramic domains should be selected based on the target loading and operating rate. The objective is not simply to maximize porosity, but to establish continuous and sufficiently accessible transport pathways throughout the active electrode volume. This becomes increasingly important as electrodes move from low laboratory loadings toward higher loadings, where transport limitations may become more severe unless the pathway design is adapted accordingly (Kress et al., 2026; Z.-H. Huang et al., 2018). Evidence from porous-carbon transport studies supports assessing pathway connectivity, but does not, by itself, predict the magnitude of improvement in a ceramic–carbon hybrid.

9.3. Evaluate Interface Function Rather Than Area Alone

The ceramic–carbon interface should be designed as a functional region rather than evaluated only by its geometric area. Effective interfaces should simultaneously support electronic coupling, maintain access to the electrolyte, and facilitate the interfacial reactions responsible for charge storage.

This distinction is important because increasing interface density does not automatically produce proportional improvement in utilization. Excessive interfacial area may even be associated with poorly connected or inaccessible regions if the surrounding architecture does not provide effective transport pathways. Interface engineering should therefore focus on interface quality and functionality, including electronic coupling, chemical compatibility, structural integrity, and accessibility, rather than interface area

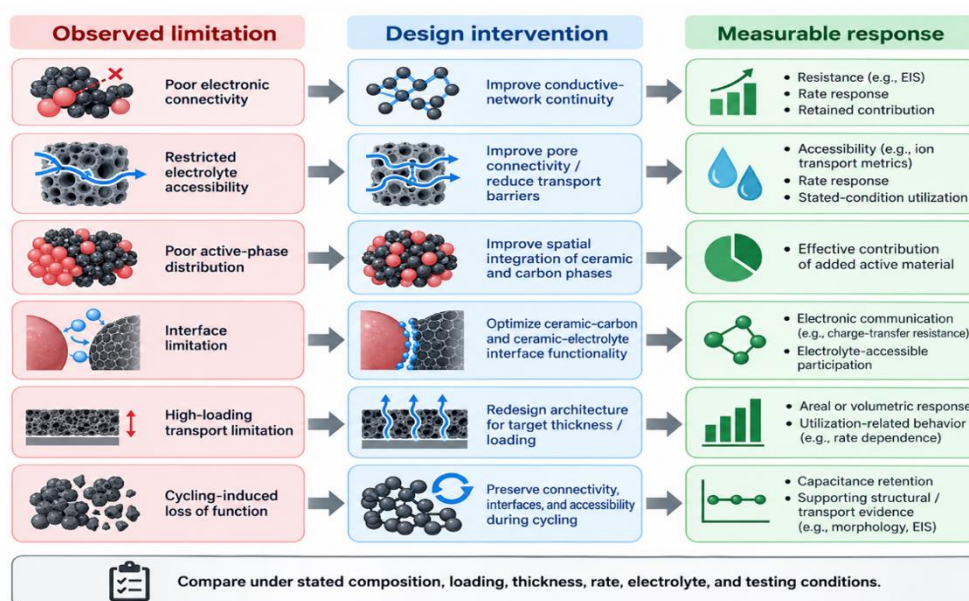


Figure 5. Design framework for ceramic-carbon hybrid supercapacitor electrodes. Observed limitations in electronic connectivity, electrolyte accessibility, active-phase distribution, interfacial function, high-loading transport, and cycling stability are linked to candidate interventions and measurable responses. Comparisons require stated composition, loading, thickness, rate, electrolyte, and testing conditions. The framework does not prescribe a universally optimal material or architecture.

alone. A claimed interface benefit should be tested against an appropriate comparison that also documents composition, loading, and architecture.

9.4. Test Whether Added Active Material Contributes

Test a series of loadings at the intended operating rate and determine whether added ceramic continues to increase the areal or volumetric response without an unacceptable loss of rate capability.

9.5. Compare Performance on a Stated Basis

Consequently, practical evaluation should consider gravimetric, areal, and, where appropriate, volumetric performance together with active-material loading, electrode thickness, operating rate, and cycling stability. This approach avoids interpreting a high $F \text{ g}^{-1}$ value obtained from a lightly loaded electrode as direct evidence of superior practical performance. More broadly, meaningful performance metrics require clear distinction between material-level and electrode/device-level quantities (Gogotsi & Simon, 2011). The mass or volume used as the denominator and the electrode or device testing configuration must be stated, as explained in Section 8.

9.6. Design for Retained Function During Cycling

An electrode architecture should not be optimized solely for its initial capacitance. The relevant design

objective is to maintain the transport pathways, interfaces, and accessibility required for active-material utilization during repeated cycling.

This consideration also changes the interpretation of cycling stability. Capacitance retention is not only a measure of material durability; it can provide indirect, non-unique evidence of whether the electrode architecture and interfaces are capable of preserving active-material accessibility and connectivity during prolonged operation. Retention alone does not identify which material or structural change caused a loss of response.

Future architectures should therefore aim to maintain stable electronic pathways, electrolyte-accessible pores, mechanically robust ceramic-carbon interfaces, and sufficiently resilient active phases during repeated cycling. Testing should examine whether the structural and transport conditions associated with the initial response are maintained alongside capacitance retention, as capacitance retention alone does not identify the degradation mechanism.

The next section therefore considers the final component of this translation framework: how degradation progressively limits the electrode's ability to express its material capability and transforms initially effective electrode architectures during long-term operation.

10. DEGRADATION AND LOSS OF TRANSLATION DURING CYCLING

The material-to-electrode translation pathway does not remain static during electrochemical operation. Structural, chemical, and interfacial changes can progressively alter the connectivity, accessibility, transport pathways, and reaction distribution established during electrode fabrication. Consequently, degradation should not be viewed solely as a loss of intrinsic material stability or a decline in measured capacitance. It can also be understood as a progressive loss of the electrode's ability to express the charge-storage capability of its active material, whereby a fraction of the active ceramic that was initially accessible and functional becomes increasingly difficult to utilize.

10.1. Degradation as a Translation Problem

In an initially well-designed hybrid electrode, the ceramic phase is integrated with the carbon framework, connected to electronic pathways, and exposed to electrolyte-accessible regions. During repeated charge-discharge cycling, however, the active phase and its surrounding environment can evolve. Dissolution, structural reconstruction, mechanical damage, pore blockage, surface modification, and loss of electronic contact are possible, system-dependent changes that may alter the conditions under which electrochemical reactions occur ([T. Wang et al., 2019](#)).

The consequence is not necessarily an immediate loss of intrinsic redox activity. Instead, degradation may initially reduce the fraction of intrinsic capability that remains accessible and utilized. A ceramic domain may retain its chemical redox functionality while becoming electronically disconnected, physically detached, or inaccessible to the electrolyte. Thus, degradation can progressively shift the electrode from a state of efficient translation toward one in which an increasing fraction of the active-material inventory becomes electrochemically ineffective.

Redox-active ceramic phases can undergo structural changes during repeated electrochemical cycling. Depending on the chemistry and operating conditions, repeated ion insertion and extraction, surface redox reactions, dissolution-redeposition processes, or local chemical transformations can modify particle morphology and pore structure.

The resulting degradation is therefore closely linked to the architecture established during electrode fabrication. A structure that initially provides short transport distances and high accessibility may gradually lose these advantages if cycling causes pore obstruction or structural collapse. Conversely, a mechanically stable architecture with robust interfacial contact may help preserve a larger fraction of the initially accessible active phase.

This highlights an important distinction between initial architecture and retained architecture. High initial capacitance demonstrates the electrode's initial response

under the specified testing conditions; long-term retention additionally requires the structural features responsible for this response to remain functional during operation.

Importantly, electronic connectivity can deteriorate without complete physical removal of the ceramic phase. A region that remains visibly present in the electrode may nevertheless contribute little to the electrochemical response if electrons can no longer reach it efficiently. This loss of utilization illustrates why post-cycling morphology alone may be insufficient to explain capacitance fading.

The functional quality of the interface should therefore be evaluated not only before cycling but also after prolonged operation. Stable interfaces can preserve electronic pathways and active-site accessibility, whereas unstable interfaces can progressively weaken the coupling between the ceramic and carbon phases.

For hybrid electrodes, this is one reason the carbon framework should be considered part of the stability-relevant architecture rather than simply a conductivity-enhancing component. Maintaining continuous electronic pathways can help preserve the electrochemical contribution of the ceramic phase as the electrode evolves during cycling ([Ren et al., 2021](#)).

10.2. Pore Blockage and Transport Degradation

Degradation can also modify the transport environment within the electrode. Surface reconstruction, dissolution products, precipitates, or accumulated reaction products may partially obstruct pores and reduce electrolyte penetration in systems where these processes occur. Even when the total pore volume remains relatively high, changes in pore connectivity can increase transport resistance and produce greater spatial heterogeneity in electrochemical activity.

One possible pathway is that reduced pore connectivity limits electrolyte access and changes where reactions occur, thereby decreasing the contribution of some active regions to measured capacitance. This sequence is a mechanistic hypothesis for a particular electrode until the intermediate changes are supported by measurements.

10.3. Chemical Change and Loss of Active Inventory

Chemical instability represents another direct pathway to performance loss. Redox-active ceramic phases may undergo dissolution, chemical transformation, or surface reconstruction depending on their composition, electrolyte, potential window, and operating conditions. When active material is physically lost from the electrode, the available charge-storage inventory decreases directly.

Synthesis-driven reconstruction into Ni/Co-OOH structures on doped carbon illustrates that the identity of

an active phase can depend on its preparation and transformation history ([Hou et al., 2020](#)). Consequently, the phase initially incorporated into an electrode should not automatically be equated with the phase responsible for charge storage during operation.

From the translation perspective, chemical degradation is important not only because it may reduce the quantity of active material, but also because it can redistribute or transform the active phase in ways that reduce its effective utilization.

This possibility is particularly relevant to thick or highly loaded electrodes, where spatial differences in ionic and electronic transport may exist even before cycling. If regions with more efficient transport pathways account for a disproportionate share of the electrochemical reaction, they may experience greater local chemical and structural stress. Degradation can then reinforce the initial reaction heterogeneity rather than simply reduce overall activity uniformly. Thickness alone, however, does not establish that this spatial sequence occurs in a given electrode.

A capacitance-retention percentage or a post-cycling image alone cannot identify the operative degradation pathway; targeted electrochemical and materials characterization is needed to distinguish among possible causes ([Semente et al., 2026](#); [T. Wang et al., 2019](#)).

Cycling response need not involve a simple, monotonic loss of capacitance: a study of Mn_2O_4 /reduced graphene oxide reported capacitance above its initial value after extended cycling ([Xiong et al., 2017](#)). Such retention behavior is an experimental observation; identifying its mechanism requires evidence beyond the retention percentage.

From this perspective, degradation represents the dynamic counterpart of material-to-electrode translation. Fabrication establishes an initial translation pathway, while electrochemical operation continuously tests whether that pathway can be maintained. Cycling can therefore modify the same structural and functional conditions that initially enabled active-material participation.

This dynamic perspective provides the basis for the final discussion of research directions. The remaining challenge is to move beyond empirical optimization of individual material and structural parameters toward predictive strategies that can identify, quantify, and minimize translation losses throughout the lifetime of hybrid supercapacitor electrodes.

11. OUTLOOK AND RESEARCH DIRECTIONS

The following research directions focus on how to identify translation losses, test the proposed design principles, and validate electrode benefits under practical conditions.

11.1. From Empirical Optimization to Translation-based Design

Much of the development of ceramic-carbon hybrid electrodes has relied on empirical optimization of composition, morphology, synthesis conditions, and carbon content. Although this approach has produced substantial improvements in reported capacitance, it provides limited predictive understanding of why a particular architecture performs well or under which conditions its advantages will persist.

Future studies should therefore place greater emphasis on identifying causal relationships between material properties and electrode-level outcomes. Rather than asking only whether a structural modification increases capacitance, it is more informative to determine whether the modification improves electronic connectivity, electrolyte accessibility, reaction distribution, active-material utilization, or degradation resistance, and whether these benefits persist at higher loadings and operating rates. Matched electrode series, with the modified design variable and measurement conditions clearly specified, would make these explanations more testable.

11.2. Defining and Estimating Active-material Utilization

Active-material utilization is central to the material-to-electrode translation problem, yet it remains difficult to quantify directly under specified operating conditions. The mass of ceramic incorporated into an electrode is readily measured, whereas the fraction that is electrochemically active at a given rate, loading, and state of charge is considerably more difficult to determine. As discussed in Section 7, quantifying utilization as a numerical fraction also requires an explicit reference for the potentially available charge; incorporated mass alone does not provide this reference.

Future work should therefore develop experimentally accessible approaches for estimating the active phase's condition-dependent contribution and, where possible, its spatial and temporal variation. Combining electrochemical measurements with operando spectroscopy, imaging, tomography, or chemical mapping could help identify which regions of an electrode participate in charge storage and how their contributions change with operating conditions. However, a map of morphology or electrolyte distribution is not, by itself, a map of locally stored charge.

The utilization challenge discussed by [Ge et al. \(2021\)](#) motivates the development of spatially resolved measurements, although establishing local charge storage requires methods that directly probe the relevant electrochemical reactions.

11.3. Spatially Resolved and Operando Characterization

A major research direction should therefore be the integration of spatially resolved characterization with operando electrochemical measurements. Mapping electrolyte penetration, local reaction activity, phase evolution, and interfacial changes during operation could establish direct links between electrode architecture and reaction distribution. The selected method should distinguish the quantity being measured, such as structure, local chemistry, ion motion, or electrochemical response, from the utilization inferred from that measurement.

Existing studies of utilization and electrode transport motivate spatially resolved investigations, but measurements of pore structure or ion motion cannot, by themselves, identify which ceramic regions store charge. Claims about spatial reaction distribution require reaction-sensitive measurements linked to specific electrode positions and operating states ([Ge et al., 2021](#); [Kress et al., 2026](#)).

This approach is particularly important for thick and high-loading electrodes, where spatial gradients may become significant. Understanding these gradients could enable electrode architectures to be designed around measured reaction distributions, where such measurements are available, rather than relying solely on average structural parameters.

11.4. Predictive Modeling and Multiscale Approaches

A complementary research direction is the development of predictive models that connect intrinsic material properties with electrode-level performance. Existing electrochemical models can describe transport, reaction kinetics, and porous-electrode behavior, but hybrid ceramic-carbon electrodes introduce additional complexity through heterogeneous phase distributions, interfaces, pore networks, and evolving structures.

[Berrueta et al. \(2019\)](#) review supercapacitor modeling approaches and their relationship to electrical characteristics. [Drummond et al. \(2019\)](#) investigate layered-electrode designs for overcoming diffusion limitations. These studies support selecting models according to the transport or electrical response being predicted; neither establishes a measured spatial map of charge storage across all ceramic domains.

Future models should therefore move toward multiscale, experimentally constrained descriptions that connect material-level properties with electrode architecture and operating conditions. Such models could help predict how changes in ceramic loading, carbon fraction, pore connectivity, electrode thickness, or interfacial properties affect reaction distribution and utilization. A useful validation strategy would specify

predictions before comparing them with data from a separate, matched electrode series. Agreement with the data used to fit a model alone would not establish its predictive capability.

11.5. Practical Loading and Device-level Validation

The transition from low-loading laboratory electrodes to higher-loading electrodes remains one of the most important tests of material-to-electrode translation. An architecture that performs exceptionally well at low loading may not retain the same advantages as electrode thickness, active-material content, or transport distances increase.

Future research should therefore report performance across a meaningful range of mass loadings and electrode thicknesses, rather than relying primarily on optimized low-loading conditions. Areal and volumetric capacitance should be considered alongside gravimetric capacitance when assessing practical electrode performance. The mass and volume used for normalization, as well as the rate and testing configuration, must be explicitly specified and consistently applied across that range ([Gogotsi & Simon, 2011](#); [Noori et al., 2019](#)).

Equally important is validation at the device level. Three-electrode measurements can guide electrode selection, provided that loading, thickness, electrolyte, potential window, rate, and normalization basis are specified. Claims about device performance require testing a charge-balanced two-electrode cell and reporting the cell configuration, operating voltage window, and normalization basis used to calculate capacitance, energy, or power. Separator, packaging, and other inactive components must also be accounted for according to the device-level metric being reported.

Complete-cell examples include CoAl-layered double hydroxide (LDH) and rGO electrodes in a flexible asymmetric device ([S. Li et al., 2017](#)), hematite-quantum-dot/graphene negative electrodes paired with MnO₂/graphene ([Xia et al., 2015](#)), and Ni(OH)₂/graphene paired with porous graphene ([Yan et al., 2012](#)). The broader asymmetric-supercapacitor literature discusses electrode selection together with operating-window and performance-evaluation considerations ([Shao et al., 2018](#)). These cell demonstrations complement, rather than replace, matched electrode-level comparisons.

For asymmetric supercapacitors, the negative electrode need not be restricted to activated carbon; earth-abundant alternatives have been examined specifically for this role ([Rahmanifar et al., 2019](#)). Nano-architected Ni(OH)₂/carbon-nanotube electrodes provide a further asymmetric-cell example ([Tang et al., 2012](#)). Charge balance and the stable potential range of each electrode remain essential when interpreting the complete device.

Table 3. Evidence-based translation map for ceramic–carbon hybrid electrodes. The rows connect each translation stage to a possible loss, a design variable, and evidence needed to evaluate it. Representative references support mechanisms or system-specific examples; the table does not define or validate a universal numerical translation-efficiency metric.

Translation stage	Dominant mechanism	Main translation loss	Design variable	Evidence/metric	Representative references
Intrinsic charge-storage potential	Redox chemistry, ion accommodation, surface activity	Inactive or kinetically inaccessible sites	Composition, defects, phase chemistry	Storage mechanism; defined reference capacity or capacitance	(Augustyn et al., 2014; Brousse et al., 2015; Conway, 1999)
Hybrid integration	Electronic percolation and phase coupling	Poor contact or excessive carbon dilution	Carbon fraction, bonding, dispersion	Conductivity; EIS; composition	(H. Wang & Dai, 2013; H.-W. Wang et al., 2011; Zhi et al., 2013)
Architecture	Spatial organization and path length	Dead zones and long transport distances	Pore hierarchy, thickness, loading	Tortuosity; thickness dependence	(H. Jiang et al., 2013; Yuan et al., 2024; Z.-H. Huang et al., 2018)
Interface quality	Charge transfer and interfacial coupling	High local resistance or weak adhesion	Interface chemistry and heterostructure	Rct; cycling stability	(H. Yang et al., 2023; Jia et al., 2018; Tomboc et al., 2020)
Ion/electron transport	Coupled migration through solid and pores	Concentration polarization and resistive loss	Pore connectivity, tortuosity, carbon network	Rate capability; EIS	(C. Wang et al., 2026; Forse et al., 2017; Kress et al., 2026)
Electrolyte accessibility	Wet-out and access to active sites	Geometrically present but electrochemically inaccessible material	Pore size/connectivity and wettability	Rate dependence; utilization	(Béguin et al., 2014; Chmiola et al., 2006; Largeot et al., 2008; Lv et al., 2017)
Reaction distribution	Spatially heterogeneous reaction activity	Underused electrode regions	Architecture and local transport	Spatially resolved reaction-sensitive signal at a defined electrochemical state	(Forse et al., 2017; Ge et al., 2021; Kress et al., 2026)
Active-material utilization	Fraction of mass contributing to response	Inactive mass fraction	Loading, thickness, accessibility	Areal/gravimetric comparison	(Ge et al., 2021; Mazloomian et al., 2026; Z.-H. Huang et al., 2018)
Practical capacitance	Mass/area/volume-normalized electrode response	Metric inflation at low loading	Reporting basis and realistic loading	$F\text{ g}^{-1}$, $F\text{ cm}^{-2}$, $F\text{ cm}^{-3}$	(Gogotsi & Simon, 2011; H. Ma et al., 2017; Noori et al., 2019; Stoller & Ruoff, 2010)
Degradation	Structural/interface/transport evolution	Progressive loss of connectivity and accessibility	Robust interfaces and pore stability	Retention plus post/operando analysis	(Semente et al., 2026; T. Wang et al., 2019; Xiong et al., 2017)
Device validation	Electrode balancing and complete-cell constraints	Translation loss beyond three-electrode tests	Voltage window, balancing, inactive components	Device energy/power and lifetime	(S. Li et al., 2017; Shao et al., 2018; Yan et al., 2012)

11.6. Standardization of Performance Reporting

Future studies should apply the reporting criteria summarized in Section 8 consistently to electrode-level and complete-cell results so that the basis of each comparison is traceable.

Best-practice guidance for ultracapacitor materials emphasizes that electrode tests and complete-device tests address different questions (Stoller & Ruoff, 2010). Reporting the test configuration and normalization basis is therefore essential before comparing electrode-level values with device-level energy or power metrics.

Such standardization would reduce the risk of interpreting exceptionally high gravimetric capacitance as evidence of superior practical performance when the

result primarily reflects low loading or highly favorable testing conditions (Gogotsi & Simon, 2011).

The long-term opportunity is to establish a more predictive approach to hybrid supercapacitor development in which intrinsic material properties are treated as inputs to an engineered translation pathway rather than as direct proxies for practical performance. In this approach, material selection would be coupled from the outset with integration strategy, architecture, interface design, transport requirements, target loading, and anticipated degradation mechanisms.

Such a framework could reduce reliance on empirical optimization and enable more systematic identification of the mechanisms responsible for translation losses. Ultimately, progress may depend on both improved active materials and electrode designs that preserve a

substantial, experimentally supported contribution from the active phase under practical operating conditions.

Table 3 translates the proposed pathway into testable questions by pairing each potential source of loss with a design variable, an observable outcome, and the limitations of the supporting evidence.

The design implications in Table 3 are conditional: each proposed intervention requires a measured response under comparable electrode and testing conditions. The reaction-distribution row specifies a measurement requirement; the cited utilization and transport studies do not directly establish a spatial map of charge storage in ceramic domains.

12. CONCLUSIONS

The performance of ceramic-carbon hybrid supercapacitor electrodes cannot be understood solely in terms of the intrinsic charge-storage capability of their active materials. The central conclusion of this review is that intrinsic material properties and practical electrode capacitance are separated by a multiscale translation pathway in which hybrid integration, architecture, interfaces, transport, electrolyte accessibility, reaction distribution, and active-material utilization collectively influence the measured electrode response under specified conditions.

Within this framework, carbon is not simply a conductive additive. Its spatial integration with the ceramic phase can establish electronic connectivity, influence electrolyte accessibility, define transport pathways, and help maintain the active-material network. Similarly, architecture and interfaces should not be treated as secondary structural features; they are functional elements that influence which active regions remain connected and accessible during operation.

The review further highlights that active-material utilization is an electrode-level outcome rather than an intrinsic material constant. High theoretical or intrinsic charge-storage capability can be substantially reduced by limited accessibility, transport resistance, incomplete electronic connectivity, or heterogeneous reaction distribution. Consequently, increasing the amount of redox-active ceramic does not necessarily produce a proportional increase in practical capacitance. High mass loading, increased electrode thickness, and high operating rates provide particularly stringent tests of whether material-to-electrode translation remains effective. A numerical utilization fraction, however, requires an explicitly defined reference for potentially available charge and cannot be inferred from loading or capacitance alone.

Finally, degradation should be regarded as a potential change in both the active-material inventory and the conditions that allow that material to contribute. Structural reconstruction, pore blockage, dissolution, interfacial degradation, and loss of electronic

connectivity can progressively reduce accessibility and utilization during cycling. A decrease in capacitance retention alone cannot identify the dominant degradation mechanism. The ultimate objective of hybrid-electrode design should therefore be to achieve a favorable initial response while maintaining stable electrode performance at the intended loading and operating rate.

The perspective developed in this review shifts the emphasis from isolated material optimization toward translation-aware electrode engineering. Future advances will depend on linking intrinsic material chemistry with functional hybrid integration, spatially controlled architecture, interfacial design, transport and reaction mapping, utilization quantification, realistic loading, and long-term stability. Such an approach can provide a more rigorous basis for designing ceramic-carbon hybrid electrodes whose electrochemical performance is interpretable at the electrode level and, when evaluated in complete cells, relevant at the device level. The proposed framework organizes these comparisons and testable questions, but its predictive value remains to be established through controlled electrode series.

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